THE HYDROGEN ECONOMY: OPPORTUNITIES, COSTS, BARRIERS, AND R&D NEEDS

Michael Ramage, Chair
Committee on Alternatives & Strategies for Future Hydrogen Production and Use

Board on Energy & Environmental Systems
Division on Engineering & Physical Sciences
National Research Council
National Academy of Engineering

Full report available at <www.nap.edu>

COMMITTEE ON ALTERNATIVES AND STRATEGIES FOR FUTURE HYDROGEN PRODUCTION AND USE

MICHAEL P. RAMAGE, NAE,[1] Chair, ExxonMobil Research and Engineering Company (retired), Moorestown, New Jersey

RAKESH AGRAWAL, NAE, Air Products and Chemicals, Inc., Allentown, Pennsylvania

DAVID L. BODDE, University of Missouri, Kansas City

ROBERT EPPERLY, Consultant, Mountain View, California

ANTONIA V. HERZOG, Natural Resources Defense Council, Washington, D.C.

ROBERT L. HIRSCH, Scientific Applications International Corporation, Alexandria, Virginia

MUJID S. KAZIMI, Massachusetts Institute of Technology, Cambridge

ALEXANDER MacLACHLAN, NAE, E.I. du Pont de Nemours & Company (retired), Wilmington, Delaware

GENE NEMANICH, Independent Consultant, Sugar Land, Texas

WILLIAM F. POWERS, NAE, Ford Motor Company (retired), Ann Arbor, Michigan

MAXINE L. SAVITZ, NAE, Consultant (retired, Honeywell), Los Angeles, California

WALTER W. (CHIP) SCHROEDER, Proton Energy Systems, Inc., Wallingford, Connecticut

ROBERT H. SOCOLOW, Princeton University, Princeton, New Jersey

DANIEL SPERLING, University of California, Davis

ALFRED M. SPORMANN, Stanford University, Stanford, California

JAMES L. SWEENEY, Stanford University, Stanford, California

[1] NAE = Member, National Academy of Engineering

OUTLINE

- FOCUS OF THE COMMITTEE’S STUDY
- IMPLICATIONS FOR NATIONAL GOALS
- R&D PRIORITIES
- CRITERIA FOR THE TRANSITION
- MAJOR RECOMMENDATIONS
  - Systems Analysis of U.S. Energy Options
  - Fuel Cell Vehicle Technology
  - Infrastructure
  - Transition
  - Safety
  - Carbon-dioxide free hydrogen
  - Carbon capture and storage
  - DOE’s Hydrogen RD&D
- FRAMEWORK FOR ANALYSIS

FOCUS OF THE COMMITTEE'S STUDY

- Assessed the current state of technology for hydrogen production and use – focused on transportation (LDV)
- Evaluated potential future hydrogen technologies
- Estimated current and future projected costs, carbon dioxide (CO_2) emissions, and energy efficiencies
- Developed scenarios for future light-duty vehicles and associated impacts on oil imports & CO_2 emissions
- Addressed infrastructure issues
- Reviewed RD&D plan for hydrogen and recommended changes to DOE

IMPLICATIONS FOR NATIONAL GOALS

- Hydrogen could fundamentally transform the U.S. energy system
  - Enhance energy security
  - Reduce CO_2 and criteria emissions
- Therefore, a robust, ongoing hydrogen program is important
- Hurdles to a hydrogen economy are more than technical and economic, also social and political
- Natural Gas, as a hydrogen source, is a significant energy security issue
- RD&D can potentially overcome the technical and economic hurdles
- The U.S. must maintain a robust, balanced energy RD&D program in areas other than hydrogen

R&D PRIORITIES

Criteria To Judge Hydrogen Program Direction

- Technologies that could significantly impact U.S. energy security and CO_2 emissions
- The time scale for the evolution of the hydrogen economy
- Technology developments needed for both the transition period and steady state
- Social and political issues that could slow technology implementation
- DOE's role in hydrogen research and development

R&D PRIORITIES

For a viable hydrogen transportation system to emerge, the following four technological and economic challenges need priority:

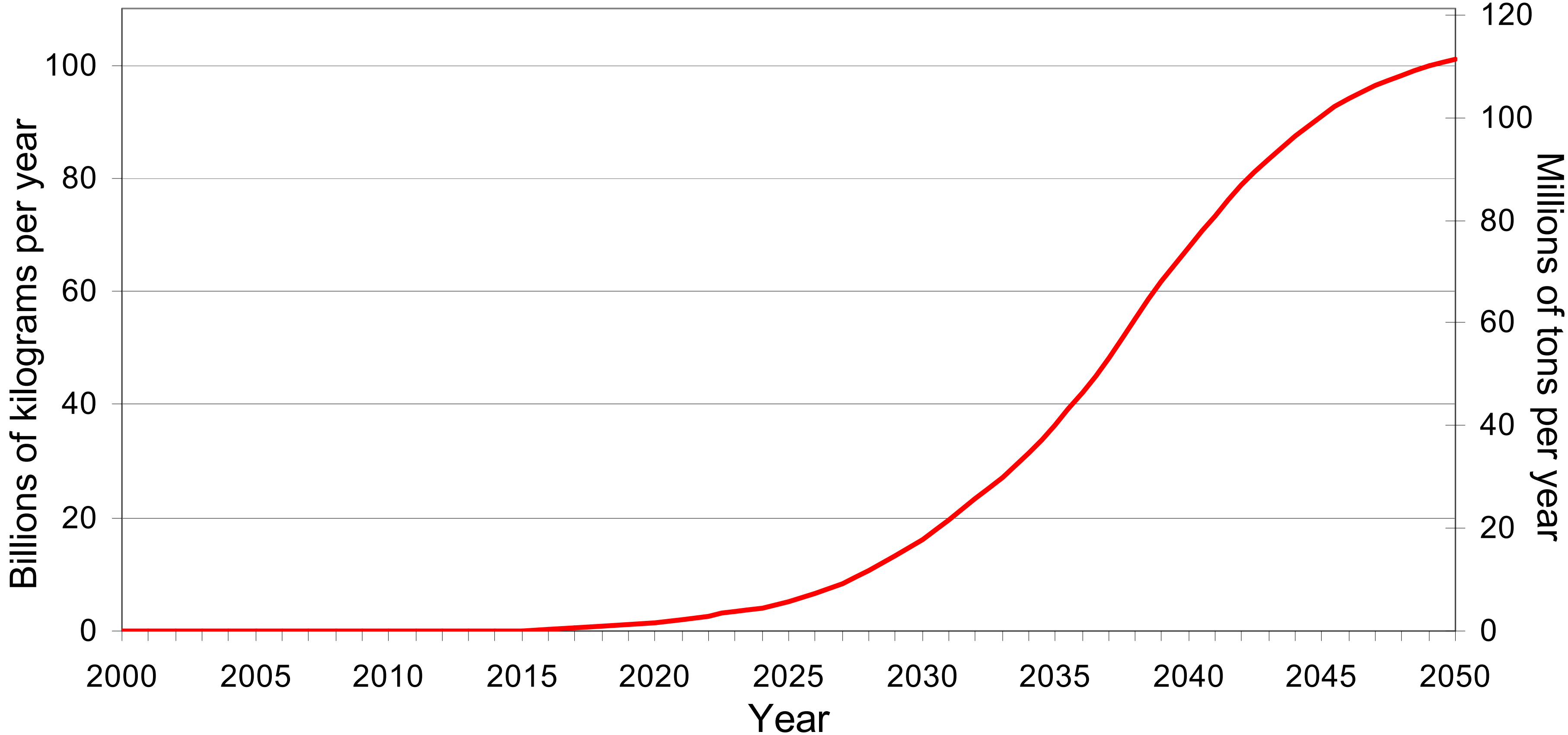
1. *Development and introduction of cost-effective, durable, safe, and environmentally desirable fuel cell systems and hydrogen storage systems for LDV*

2. *Development of the infrastructure to provide hydrogen for the light-duty vehicle user*

3. *Reduction in the costs of hydrogen from renewables*

4. *Viable CO_2 capture and storage, particularly for coal*

HYDROGEN PENETRATION SCENARIO



CRITERIA FOR THE TRANSITION
A Strategy

- Best accomplished initially through distributed production at fueling site
- Use natural gas reforming or electrolysis
- Wind or solar energy might provide electricity → onsite hydrogen
- Structure of mature hydrogen economy is difficult to imagine – let it evolve, plan the transition
- Allows time for development of new technologies/ breakthroughs/concepts for large scale hydrogen production and infrastructure
- Allows time for the market to develop and non technical hurdles to be overcome

MAJOR RECOMMENDATIONS
Systems Analysis of U.S. Energy Options

- DOE should develop and employ systems analysis
  - Short, medium, and long term
  - Implement for all U.S. energy options
  - Systems analysis effort should be independent of hydrogen program
- DOE should identify/utilize systems management approaches used elsewhere in government
- Program plan should be reviewed and updated regularly

MAJOR RECOMMENDATIONS
Fuel Cell Vehicle Technology

- DOE should emphasize breakthrough research in PEMFC
  - On-board storage systems
  - Fuel cell costs
  - Materials for durability
  - Functionality
- DOE should discontinue work on compression and cryogenic approaches to on-board storage
- Sponsor independent lessons learned study on past alternative fuels programs
- Discontinue PEM stationary RD&D and reallocate $ to FCV

MAJOR RECOMMENDATIONS
Infrastructure

- DOE infrastructure program requires greater emphasis and support
- Technical program should focus on materials issues
- Create better linkages between programs in large-scale and small-scale hydrogen production
- Clarify conditions under which large-scale and small-scale hydrogen production will become competitive, complementary, or independent
- Needs additional funding for exploratory research on new concepts for hydrogen delivery

MAJOR RECOMMENDATIONS
Transition

- Strengthen DOE's policy analysis capability with respect to the hydrogen economy
- Increase understanding of government role in facilitating industry investments
- Increase R&D on distributed small-scale natural gas and water electrolysis
- Initiate a program to develop new concepts in distributed production systems

MAJOR RECOMMENDATIONS
Safety

- Propose and discuss safety policy goals early with stakeholder groups
- Continue its work with standards development organizations
- Ensure increased emphasis on distributed production of hydrogen
- Specifically include safety in systems analysis
- Use physical testing program to resolve safety issues in advance of commercial use
- Emphasize hydrogen safety in public education programs, particularly in consumer environments

MAJOR RECOMMENDATIONS
Carbon Dioxide-Free Hydrogen

- Set more aggressive electricity cost targets for nuclear and renewable energy

- Increase emphasis on electrolyzer development by setting aggressive targets for cost reduction

- Emphasize research in direct hydrogen production

MAJOR RECOMMENDATIONS
Carbon Capture and Storage

- Tighten coupling between hydrogen program and carbon capture and storage program
- The hydrogen program should be involved in all early carbon capture and storage projects, even those that do not involve hydrogen production
- Address CO_2 infrastructure issues early in transition

MAJOR RECOMMENDATIONS
DOE's Hydrogen RD&D Plan (1 of 4)

- Continue to develop the hydrogen RD&D Plan
- Improve the integration and balance of activities among the various DOE offices
- Production/distribution/storage/dispensing portion probably underfunded – particularly with earmarked funds
- More prioritizing is needed within and across programs
- Establish more milestones and go/no-go decisions
- Adjust the program on the basis of ongoing results
- Partner with a broad range of academic, industrial, and government organizations, both domestic and international
- Establish an independent program review process and board

MAJOR RECOMMENDATIONS
DOE's Hydrogen RD&D Plan (2 of 4)

- Shift some development areas toward more exploratory work

- Establish DOE-sponsored academic energy research centers

  - Focus on interdisciplinary areas of new science and engineering with opportunities for breakthrough solutions to energy issues (e.g. materials research, nanostructures, modeling for materials design, biosciences)

MAJOR RECOMMENDATIONS
DOE's Hydrogen RD&D Plan (3 of 4)

The committee recommends increased emphasis in the following five areas:

1. *Fuel cell vehicle development*
   - R&D to facilitate breakthroughs in fuel cell costs, durability of materials, and on-board hydrogen storage systems
2. *Distributed hydrogen generation*
   - R&D in small-scale natural gas reforming, electrolysis, and new concepts for hydrogen production systems
3. *Infrastructure analysis*
   - Accelerate and increase efforts in systems modeling and analysis for hydrogen delivery to develop options and help guide R&D in large-scale infrastructure development

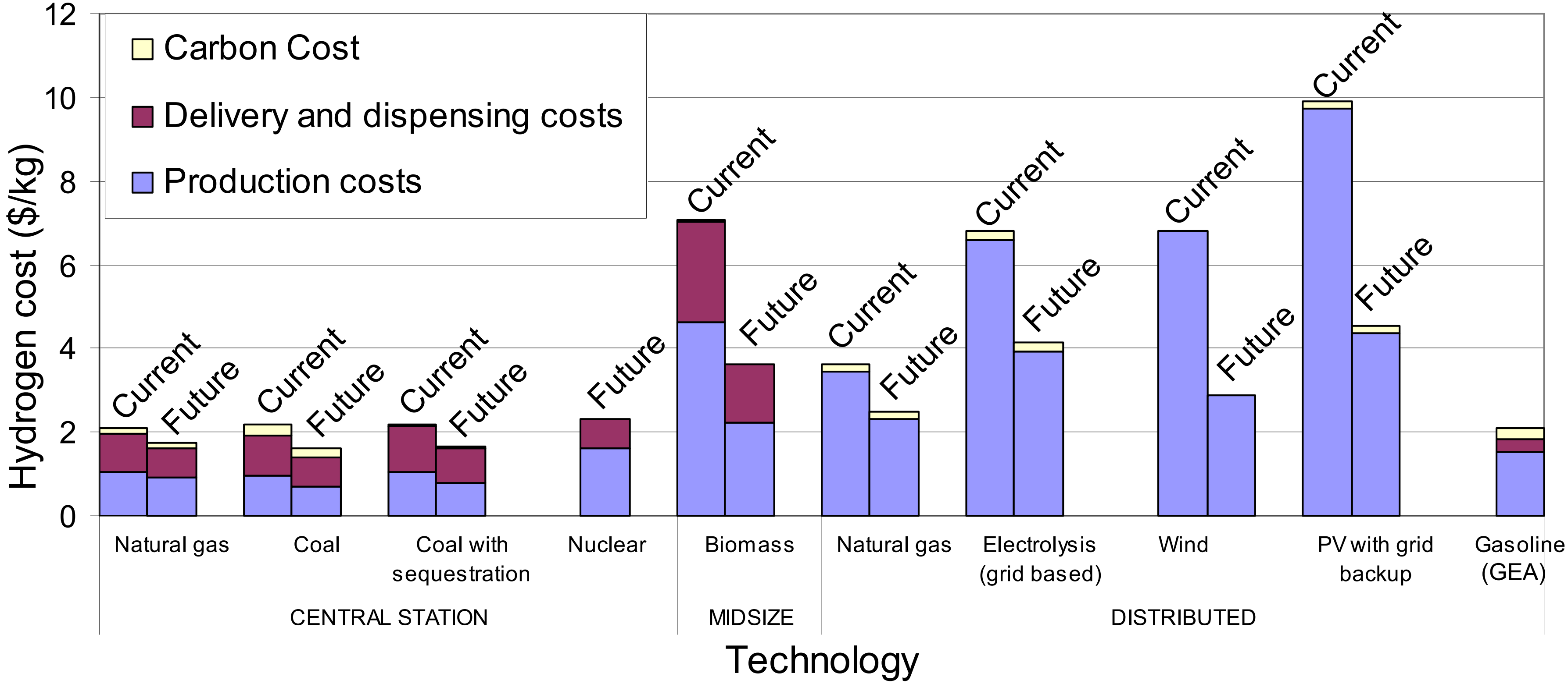
(continued)

MAJOR RECOMMENDATIONS
DOE's Hydrogen RD&D Plan (4 of 4)

4. *CO_2-free energy technologies*
   - Wind-energy-to-hydrogen for transition & potentially longer term
   - Exploratory and fundamental research on hydrogen from photobiological, photoelectrochemical, thin-film solar, and nuclear heat processes

5. *Carbon sequestration*
   - Accelerate development and early evaluation of carbon capture and sequestration
   - Continue FutureGen Project as a high-priority task

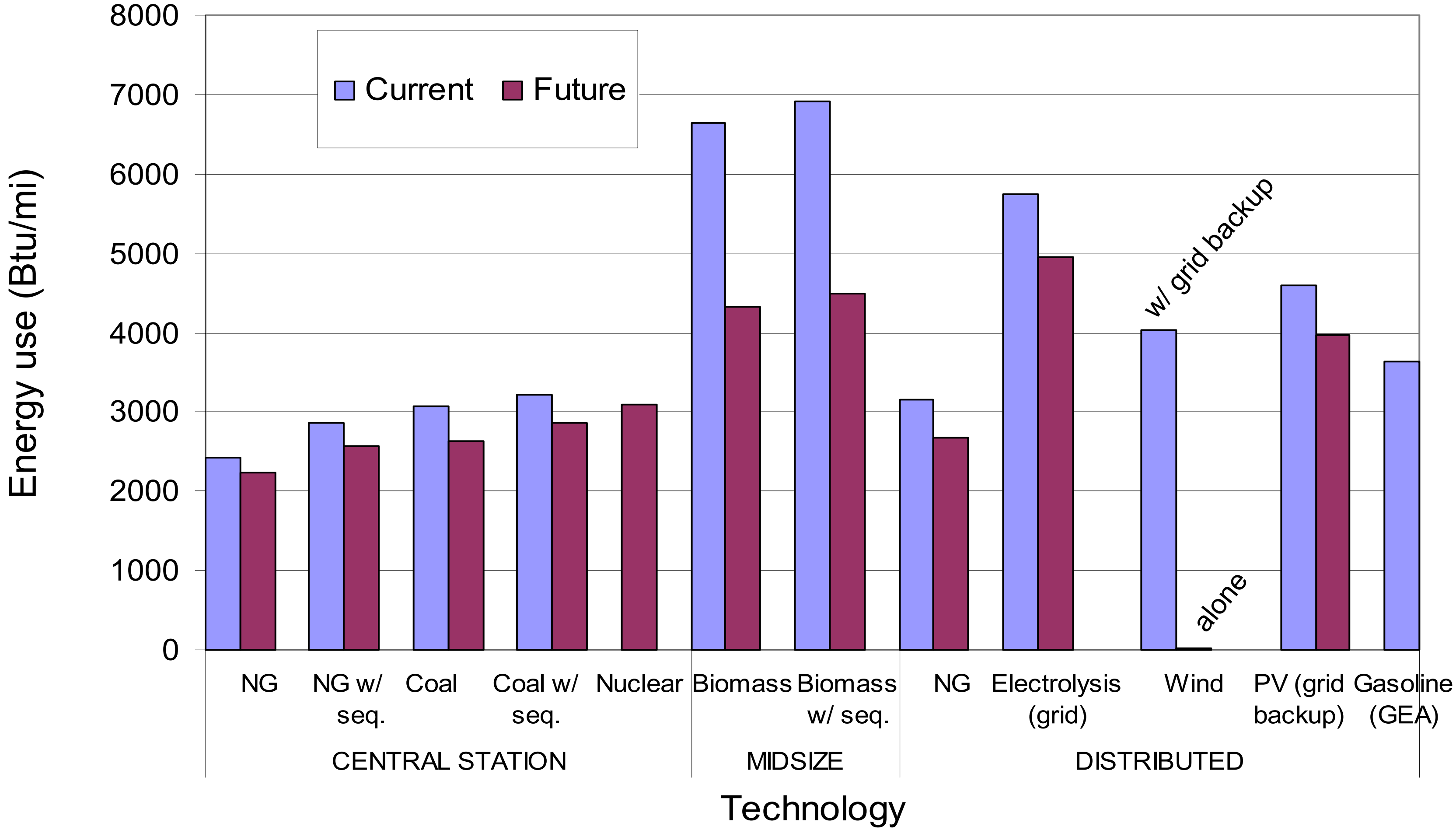
DELIVERED H_2 COSTS OF VARIOUS TECHNOLOGIES



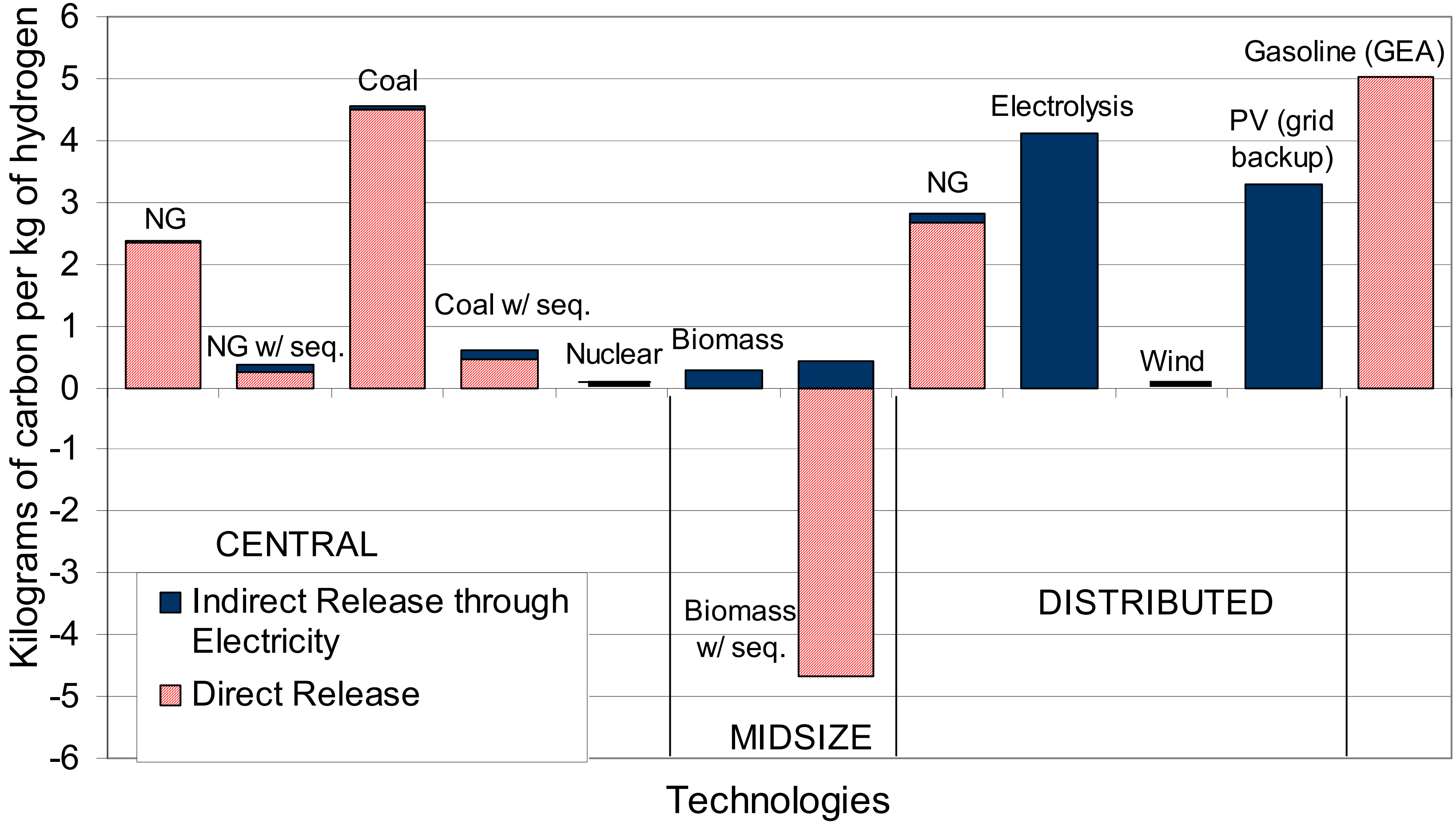
- *GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency*

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

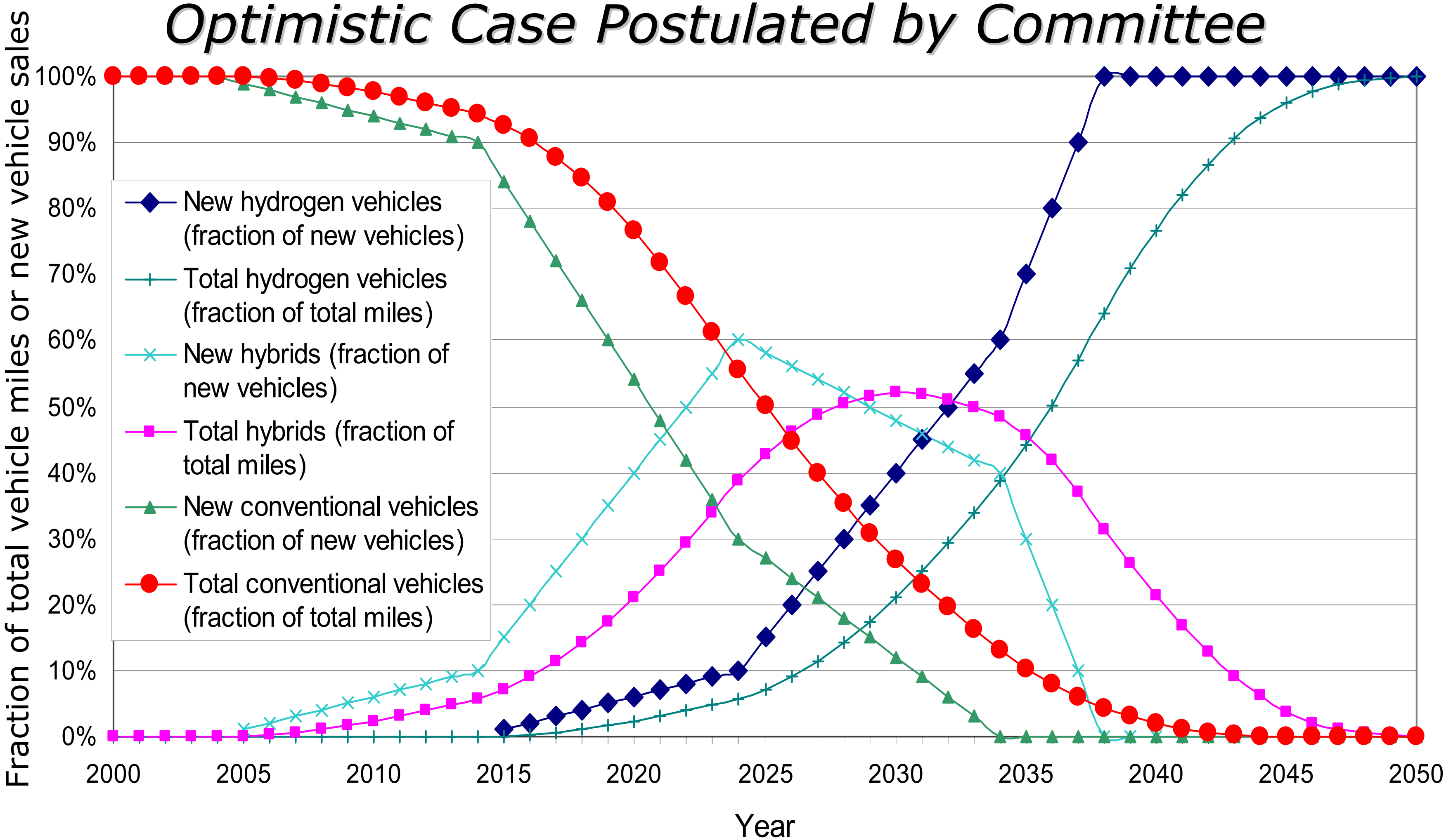
WELL-TO-WHEELS ENERGY USE



CARBON RELEASED DURING H_2 PRODUCTION, DISPENSING & DELIVERY (FUTURE TECHNOLOGIES)



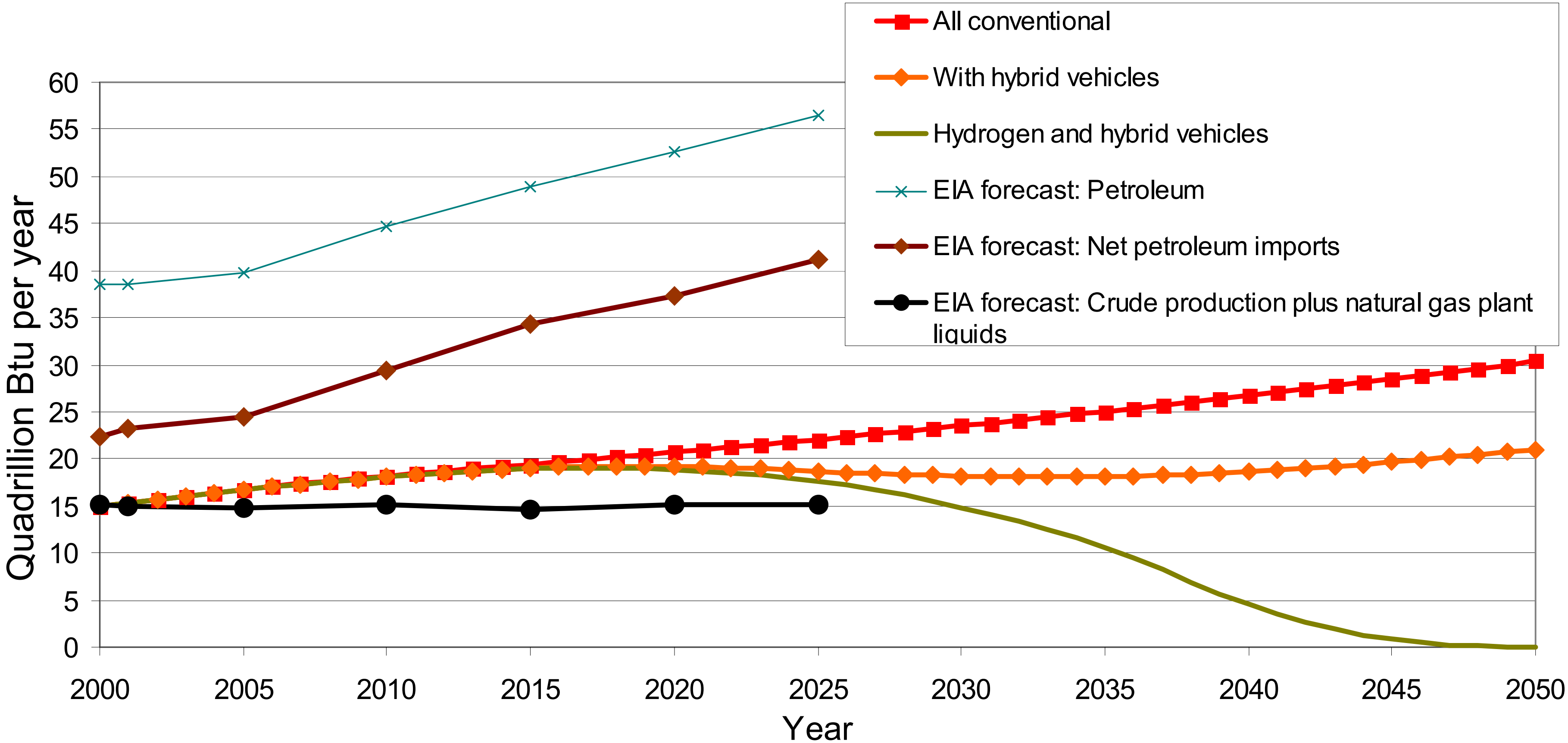
PENETRATION CURVES FOR FUEL CELL VEHICLES
Optimistic Case Postulated by Committee



- *Complete replacement of ICE vehicles with fuel cell vehicles in 2050*

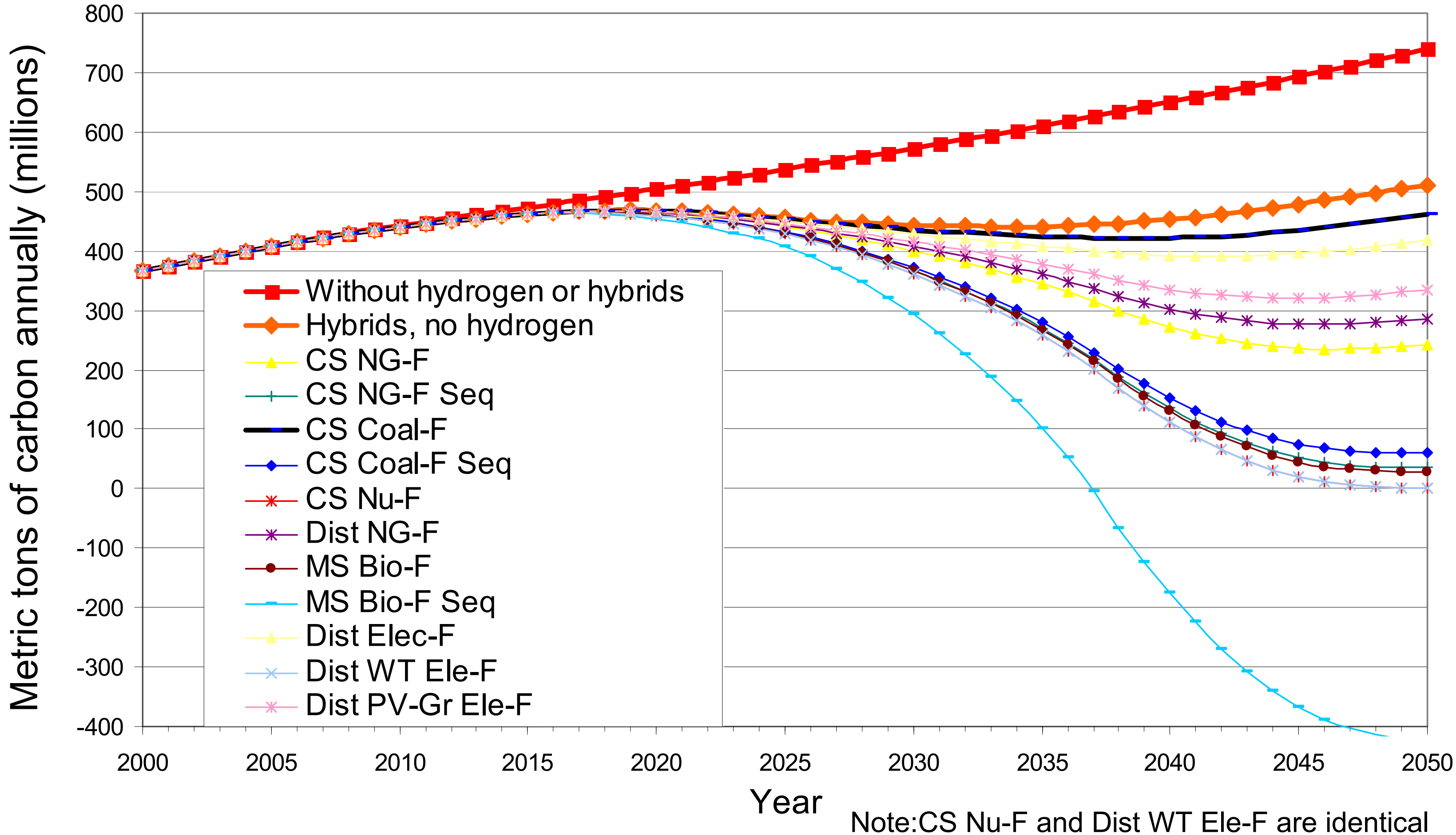
SECURITY IMPACTS

Petroleum Use Decreases with Penetration of FCV versus HEV or Conventional ICE



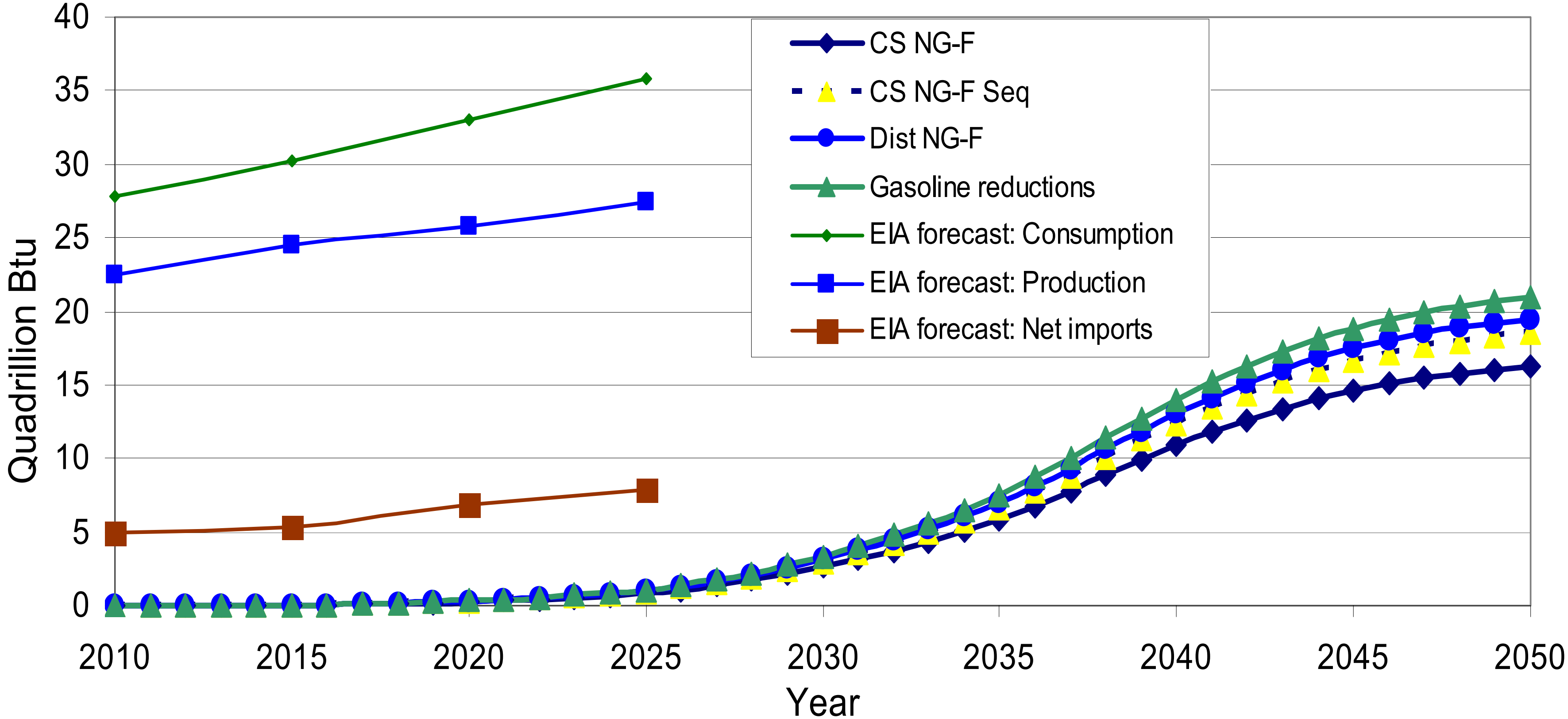
- *EIA reference projections of U.S. consumption, production, and imports of oil also shown*

IMPACT ON CARBON EMISSIONS



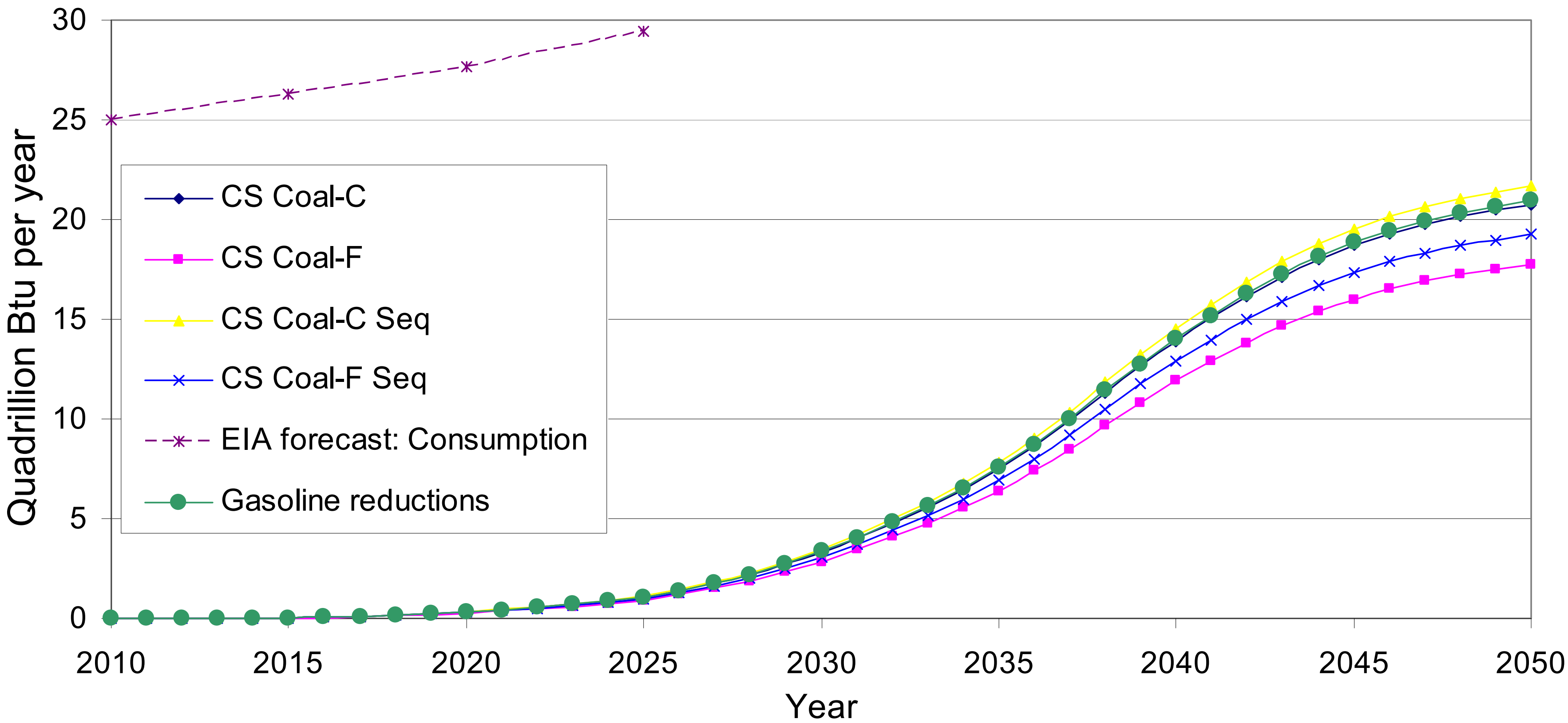
- *Curves show emissions due to H_2 supply chain for each production technology, assuming each is sole supplier of vehicles in fleet – future technology*

NATURAL GAS SMR
Energy Use and Gasoline Reductions Due to Use of H_2 in FCVs

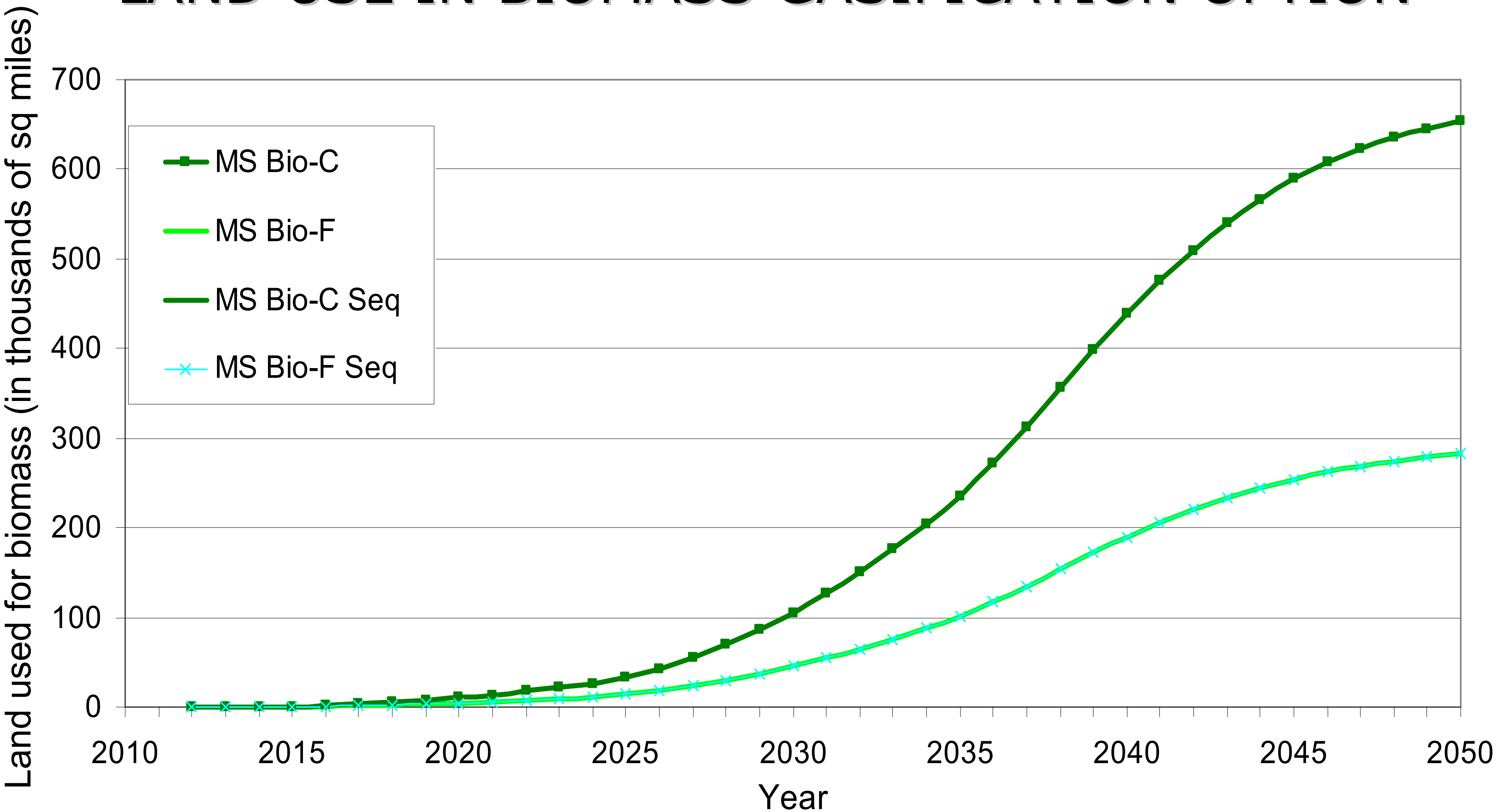


- *EIA reference projections of U.S. consumption, production and imports of oil also shown*

COAL GASIFICATION
Energy Use and Gasoline Reductions Due to Use of H_2 in FCVs

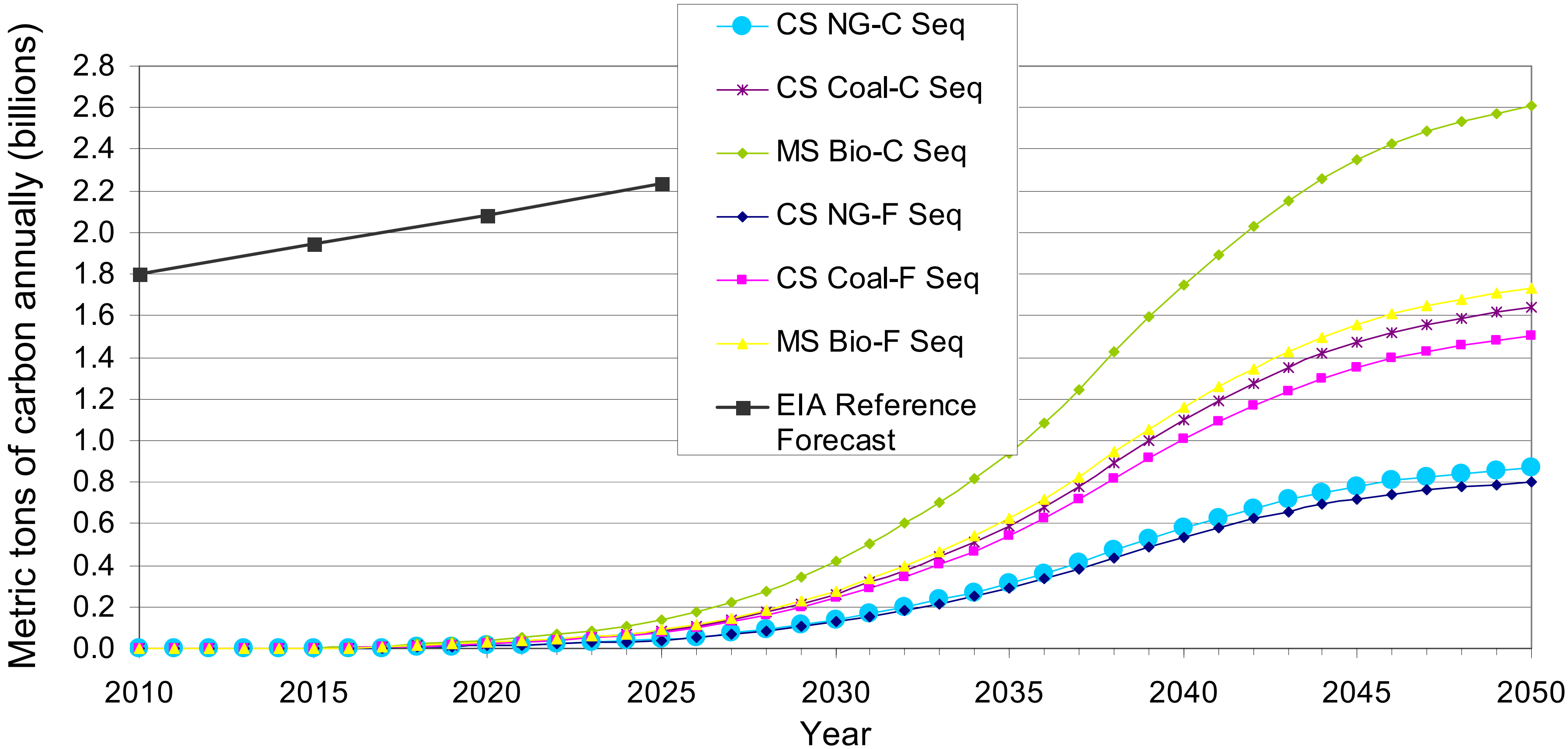


LAND USE IN BIOMASS GASIFICATION OPTION



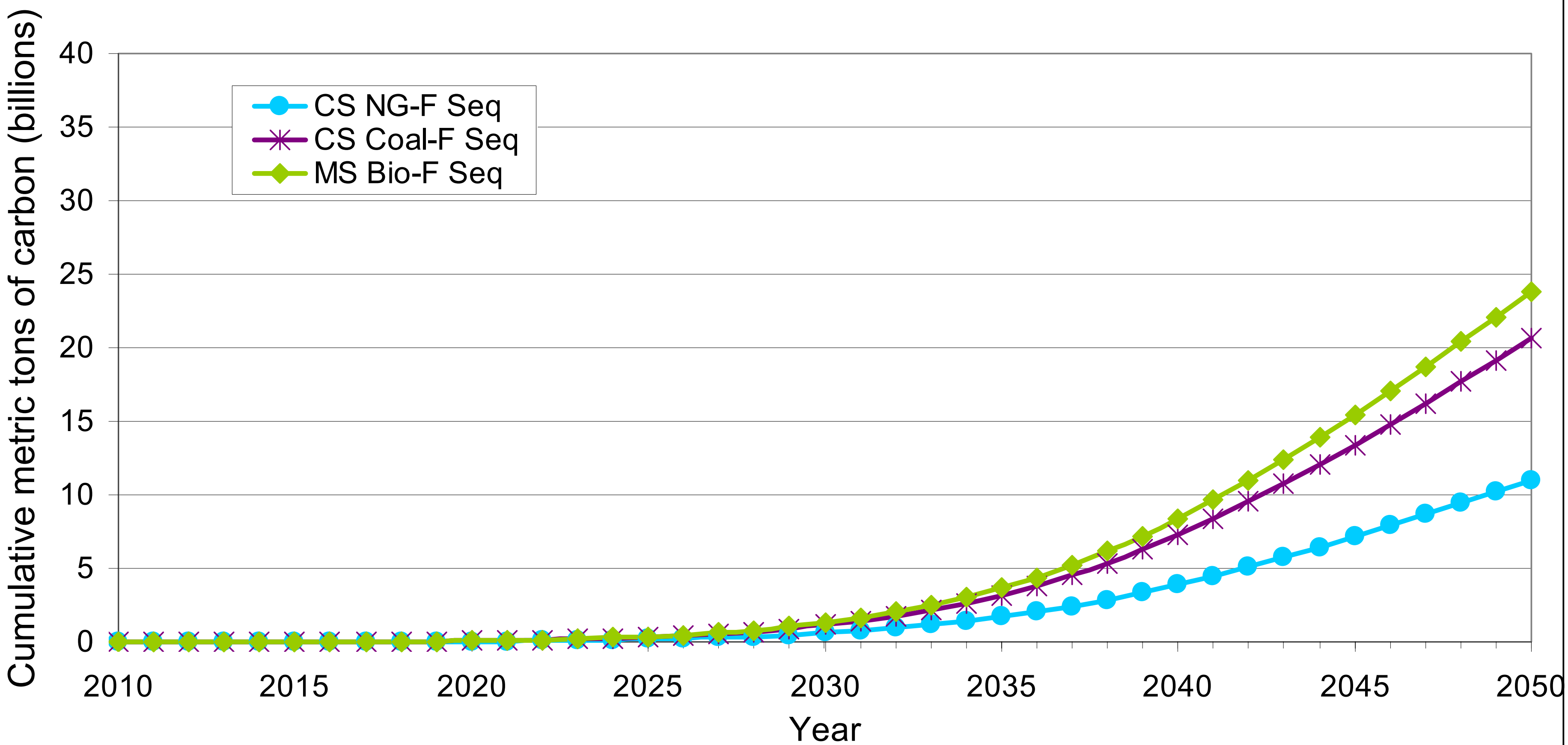
- *Currently available: 700,000 mi² cropland, 900,000 mi² pasture land*

CARBON SEQUESTRATION RATES



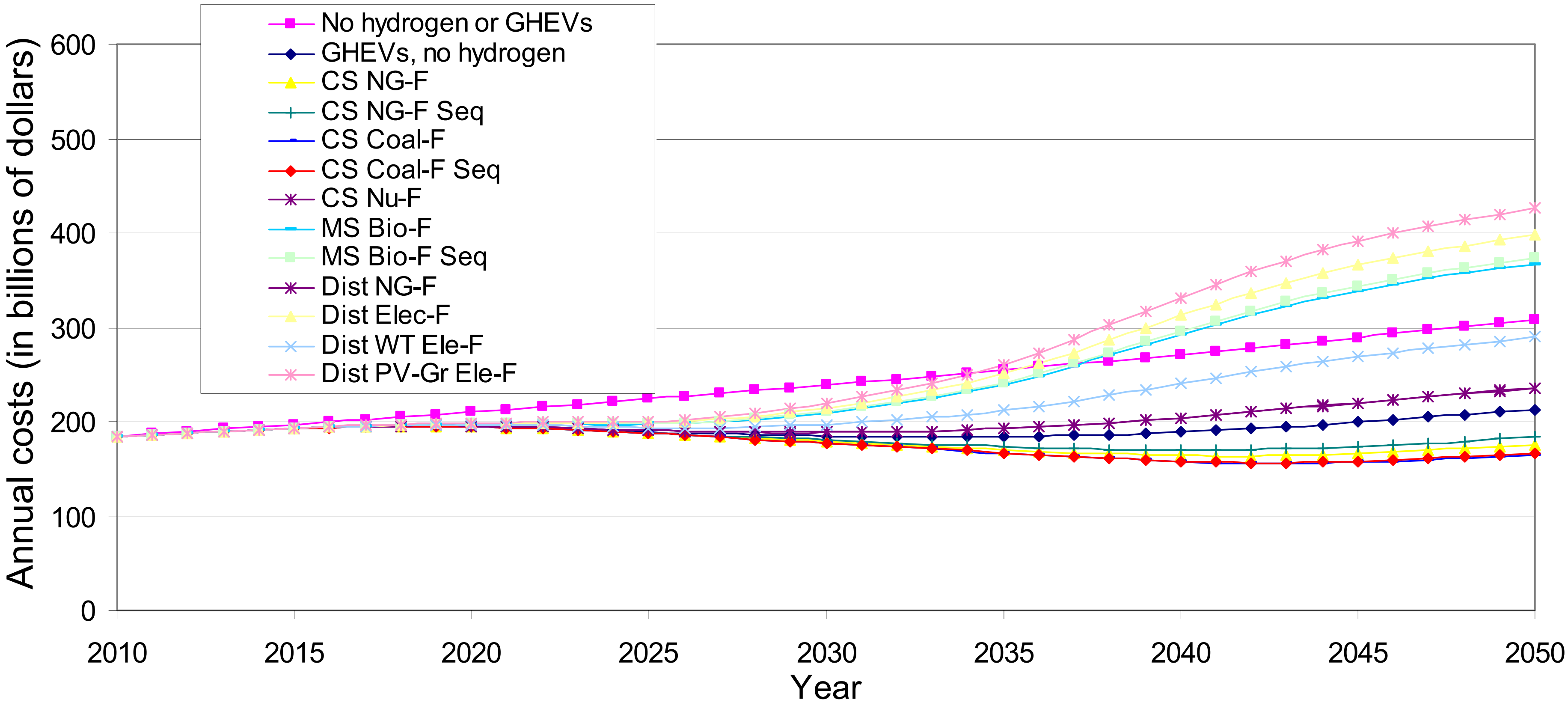
- *EIA reference forecast shown*

CUMULATIVE CARBON SEQUESTRATION



- *Capacity of depleted U.S. oil and gas reservoirs = 25-50+ billion metric tons C*
- *Capacity of unminable U.S. coal seams = 15 billion metric tons C*

SUPPLY CHAIN COSTS FOR VARIOUS H_2 PRODUCTION TECHNOLOGIES



REPORT SECTIONS

- Demand
- Storage & Infrastructure
- Carbon Capture & Storage
- Hydrogen From Natural Gas
- Hydrogen From Coal
- Hydrogen From Nuclear
- Hydrogen From Electrolysis
- Hydrogen From Wind
- Hydrogen From Biomass & Photobiological Processes
- Hydrogen From Solar
- Crosscutting Issues
  - Program Management & Systems Analysis
  - Hydrogen Safety
- Transition Matters

DEMAND SIDE
Transportation

- Only light duty highway vehicles considered
- Target: $50/kW with 4,000 – 5,000 hours of operation
- Today
  - Infrastructure: large, distributed, inexpensive, liquid fuel
  - Over 200 million vehicles need existing parallel infrastructure
  - “No compromise vehicles”: range, refueling, safety, cargo space, park anywhere
- H_2 vehicle demand won’t justify infrastructure by 2020:
  - “Best case scenario”: analogy with HEVs
  - 1st HEV in 1997; 159,100 sold world-wide by end of 2002
  - Still slow because of cost; ~ 100,000 in US in 2004
  - FCV “not close” to $100/kw today; still, assumed 1% in 2015
  - With this optimistic assumption: Less then 4 million in 2020

REPORT SECTIONS

DEMAND SIDE
Stationary

- Target: $500/kW but 40,000 – 50,000 hours
- Surveyed: central power, distributed power, industrial sector
- Fuel cells and turbines could use H_2
- To date: H_2 used mainly in industrial sector
- Emerging applications in 1 – 5000 kW area
- Multiple technologies: PEM, SOFC, MCFC

REPORT SECTIONS

DEMAND SIDE
Findings & Recommendations

- PEMFCs and storage systems have major cost, functionality, and durability problems
  - DOE should emphasize breakthrough R&D in these areas
  - Industry should fund "transition technologies"

- Major stationary FC programs not part of integrated H_2 program; companies introducing PEM
  - Discontinue PEM stationary RD&D

REPORT SECTIONS

DEMAND SIDE
Findings & Recommendations

- During past 20 years, most transportation/stationary alternative fuels and technologies programs have failed
  - Sponsor independent lessons learned study and apply to H_2 strategy
- DOE strategy does not define integrated stationary and transportation trade-offs and opportunities
  - Develop independent study for stationary systems and integrate with transportation program

REPORT SECTIONS

HYDROGEN STORAGE AND INFRASTRUCTURE

- The current energy carrier of choice is molecular hydrogen and it has the advantage that it can be produced using many feedstocks
- Significant energy lost in hydrogen distribution and dispensing
- Getting hydrogen to and on-board the vehicle in a practical manner are formidable technology challenges
  - H_2 is difficult to transmit through pipelines because of embrittlement and a propensity to leak
  - In even the best case of improved compression efficiency
    n efficiency and higher pressure on board tanks, the
    ergy, space, cost and weight penalties are formidable

    e formidable
     formidable
    formidable

REPORT SECTIONS

HYDROGEN STORAGE AND INFRASTRUCTURE
On-board Storage

- No approach to on-board storage—physical or chemical—is close to DOE/FreedomCAR target for energy density (on a total storage system basis)
- Physical storage of H_2 (i.e., pressurized, liquefied) can't reach DOE energy density target due to thermodynamic properties of H_2. Safety of high pressure storage systems may be an issue when used by untrained personnel such as consumers
- Development of new methods for carrying hydrogen, such as carbon, metal hydrides, or chemical hydrides, is needed

REPORT SECTIONS

HYDROGEN STORAGE AND INFRASTRUCTURE
Recommendations

- DOE infrastructure program requires greater emphasis and support
- Technical program should focus on materials issues
- Create better linkages between programs in large-scale and small-scale hydrogen production
- Clarify conditions under which large-scale and small-scale hydrogen production will become competitive, complementary, or independent
- Needs additional funding for exploratory research on new concepts for hydrogen delivery

REPORT SECTIONS

HYDROGEN STORAGE AND INFRASTRUCTURE
Recommendations

- Increase R&D investment in support of breakthrough approaches on small-scale electrolyzers and natural gas reformers to facilitate transition phase
- Halt efforts on high-pressure tanks and cryogenic liquid storage
  - Both approaches have reached pre-commercial development
  - Neither approach can reach DOE target for energy density
- Invest in new approaches to onboard storage of hydrogen such as solid state carriers (e.g., hydrides)

REPORT SECTIONS

CARBON CAPTURE AND STORAGE

- Fossil fuels will be one of the principal sources of hydrogen for the hydrogen economy
- Carbon capture and storage technologies will be required for successful utilization of fossil fuels in production of hydrogen

REPORT SECTIONS

CARBON CAPTURE AND STORAGE
Findings

- Only a modest incremental cost is incurred at plants that produce H_2 from coal or natural gas, if these plants also capture instead of venting the byproduct CO_2

- There appears to be abundant geological storage capacity for CO_2 below ground in hydrocarbon reservoirs and in deep brine aquifers, but sufficient storage integrity has not been established

- All CO_2 storage projects (not just hydrogen) have common and difficult institutional issues and issues of public acceptance

REPORT SECTIONS

CARBON CAPTURE AND STORAGE
Recommendations

- Integration of carbon capture and storage with H_2 production from fossil fuels starts with the integration of R&D programs
- Address CO_2 infrastructure issue early in transition
- The national H_2 R&D program should be involved in all of the early carbon capture and storage projects, even those that do not involve H_2 production, including:
  - Projects where CO_2 is captured as impurity in natural gas
  - Projects where CO_2 is captured during electricity production

REPORT SECTIONS

HYDROGEN FROM NATURAL GAS
Overview of Issues

- 95% of hydrogen today is produced by steam methane reforming (SMR)
- Distributed production of hydrogen by SMR is likely transition strategy
  - Potentially cost competitive
  - No need to create hydrogen infrastructure – makes use of existing NG infrastructure
- Potential role for natural gas conversion to supply hydrogen both in transition (small, distributed) and long term (large, centralized generators)

REPORT SECTIONS

HYDROGEN FROM NATURAL GAS
Findings

- Potentially cost competitive for distributed generation, interim source of H_2
  - Estimated cost of hydrogen from mass-produced, 480 kg/D generator, $2.33 to $3.50/kg
  - Overall efficiency 55 to 65 %
- Question applicability to long term hydrogen supply given projected increase in natural gas imports
- Current DOE program includes natural gas conversion for small, distributed units and large, centralized units:
  - Unclear whether focused on mass-produced appliances for transition
  - Appears focused on use of POX/ATR, but SMR could be preferred technology

REPORT SECTIONS

HYDROGEN FROM NATURAL GAS
Recommendations

- Focus DOE program on development of mass-produced hydrogen appliances for fueling stations:
  - Pursue two approaches (POX/ATR and SMR)
- Downsize effort on centralized generation
- Emphasize integrated fueling facility including hydrogen appliances and their ancillary sub-systems (compression, storage, controls)

REPORT SECTIONS

HYDROGEN FROM COAL
Overview of Issues

- Coal is abundant and inexpensive but has environmental issues
  - Criteria pollutants mitigated by technology choice – gasification
  - Concerns with increased mining and transportation
  - CO_2 releases highest among choices
- Coal is more a long term than short term alternate
  - Plants must be very large to achieve economies
  - Hydrogen demand must be very large to support large plants
- Gasification is commercial but coal gasification to hydrogen needs some development
  - Synergy or overlap with coal to power
  - Success in clean coal to power development and use aids hydrogen

REPORT SECTIONS

HYDROGEN FROM COAL

Findings and Recommendations

- The U.S. has vast coal resources
  - Hydrogen from coal can be inexpensive
  - Technologies need to be improved to make the process truly commercial and competitive
  - Coal must be a significant component of R&D aimed at making very large amounts of hydrogen
- There are many common technologies used in IGCC and hydrogen from coal
  - Progress in IGCC benefits hydrogen
  - Likely that the least costly hydrogen can be made at plants that co-generate both power and hydrogen
  - Both Vision 21 and coal to hydrogen programs should be funded to meet their program goals

(continued)

HYDROGEN FROM COAL
Findings and Recommendations

- Because making hydrogen from coal produces more CO_2 than from any other primary feed it is critical that carbon sequestration techniques be developed before coal is considered as a viable long term choice

- The FutureGen Project
  - To demonstrate co-producing power and hydrogen with carbon sequestration
  - This large-scale testbed for new technologies will advance the development of coal to hydrogen technology
  - Project should be pursued and the overall size and complexity closely monitored

REPORT SECTIONS

HYDROGEN FROM NUCLEAR ENERGY
Overview of Issues

- Production of hydrogen through water electrolysis is currently possible but has low energy efficiency

- More efficient hydrogen production is possible using high temperature reactors
  - Nuclear assisted SMR
  - Thermochemical water splitting
  - High temperature steam electrolysis

- High temperature reactors
  - Include gas cooled graphite moderated reactors and molten salt cooled graphite moderated reactors
  - Experience with such reactors exist at lower temperatures than ultimately desirable

REPORT SECTIONS

HYDROGEN FROM NUCLEAR ENERGY
Findings

- Lab top investigations show that thermochemical water splitting is very promising above 900°C
- Steam electrolysis can be attained at lower temperatures (700°C) and is less sensitive to temperature if coupled to a newly proposed supercritical CO_2 power conversion cycle
- Concerns about safety, waste management and proliferation could limit public acceptance

REPORT SECTIONS

HYDROGEN FROM NUCLEAR ENERGY
Recommendations

- Hydrogen production technology investigations should include both thermochemical water splitting and high temperature electrolysis of steam (HTES) and include:
  - Materials durability
  - Effects of operating conditions such as pressure
  - Effects of system integration
  - Room for innovative approaches
- Data gathering should be at a level to allow down-selection in 4 to 5 years
- Hydrogen production technologies should be supported as a small add on effort to nuclear reactor development – current budget probably too small
- Safety implications of integration of nuclear and chemical plants should be addressed

REPORT SECTIONS

HYDROGEN FROM ELECTROLYSIS
Overview

- Two main technologies: PEM and liquid electrolyte, comparable costs
- Higher temperature electrolyzers may offer higher efficiency but are less developed
- PEM electrolyzer cost reductions will derive from fuel cell cost reductions
- Electrolysis is particularly suitable for use with inherently distributed renewable technologies

REPORT SECTIONS

HYDROGEN FROM ELECTROLYSIS
Findings

- Fuel cost from electrolyzers could be competitive with other distributed-scale options for supplying hydrogen
- DOE's electrolysis program is on track, but could include:
  - Reducing parasitic energy losses
  - Reducing current density of electrolysis modules to increase efficiency
  - Development of higher temperature (hence more efficient) technology, including electrolysis/oxidation hybrid
- Electrolysis is most likely to be used in distributed-scale systems
- Electrolysis will be a key technology during the transition to a hydrogen economy and in conjunction with intermittent renewable technologies

REPORT SECTIONS

HYDROGEN FROM ELECTROLYSIS
Recommendations

- DOE's electrolysis technology program should continue to target cost reduction, enhanced system efficiency and improved durability for distributed-scale plants
- The cost targets for electrolyzers should be reduced to $125/kW and the efficiency raised to over 70% (LHV)
- Research should focus on:
  - Lower cost membranes, catalysts and other cell and system components
  - Increasing the temperature and pressure range of membranes and systems
  - Improved and lower-cost system design and integration
  - Components and systems that will enable electrolyzers to operate compatibly with intermittent renewable energy sources

REPORT SECTIONS

HYDROGEN FROM WIND ENERGY
Overview of a Distributed Source

- Production of hydrogen from renewable energy sources is often stated as the long-term goal of a mature hydrogen-based economy
  - Wind energy is one of the most cost-competitive renewable energy technologies available today
  - It is a zero emission and a domestic source of energy

- Successful development/deployment will depend on:
  - Further reduction in cost of wind electricity
  - Reductions in electrolyzer costs
  - Optimization of the turbine–electrolyzer–storage system

REPORT SECTIONS

HYDROGEN FROM WIND ENERGY
Cost and Emissions

	Current Technology		**Future Technology**	
	(w/grid back up)	(no grid back up)	(w/grid back up)	(no grid back up)
Average Cost of Electricity (cents/kWh)	6	6	4	4
Wind turbine capacity Factor (%)	30	30	40	40
Hydrogen ($/kg)	6.64	10.69	3.38	2.86
Carbon emissions (kg of C/kg of H_2)	3.35	0	2.48	0

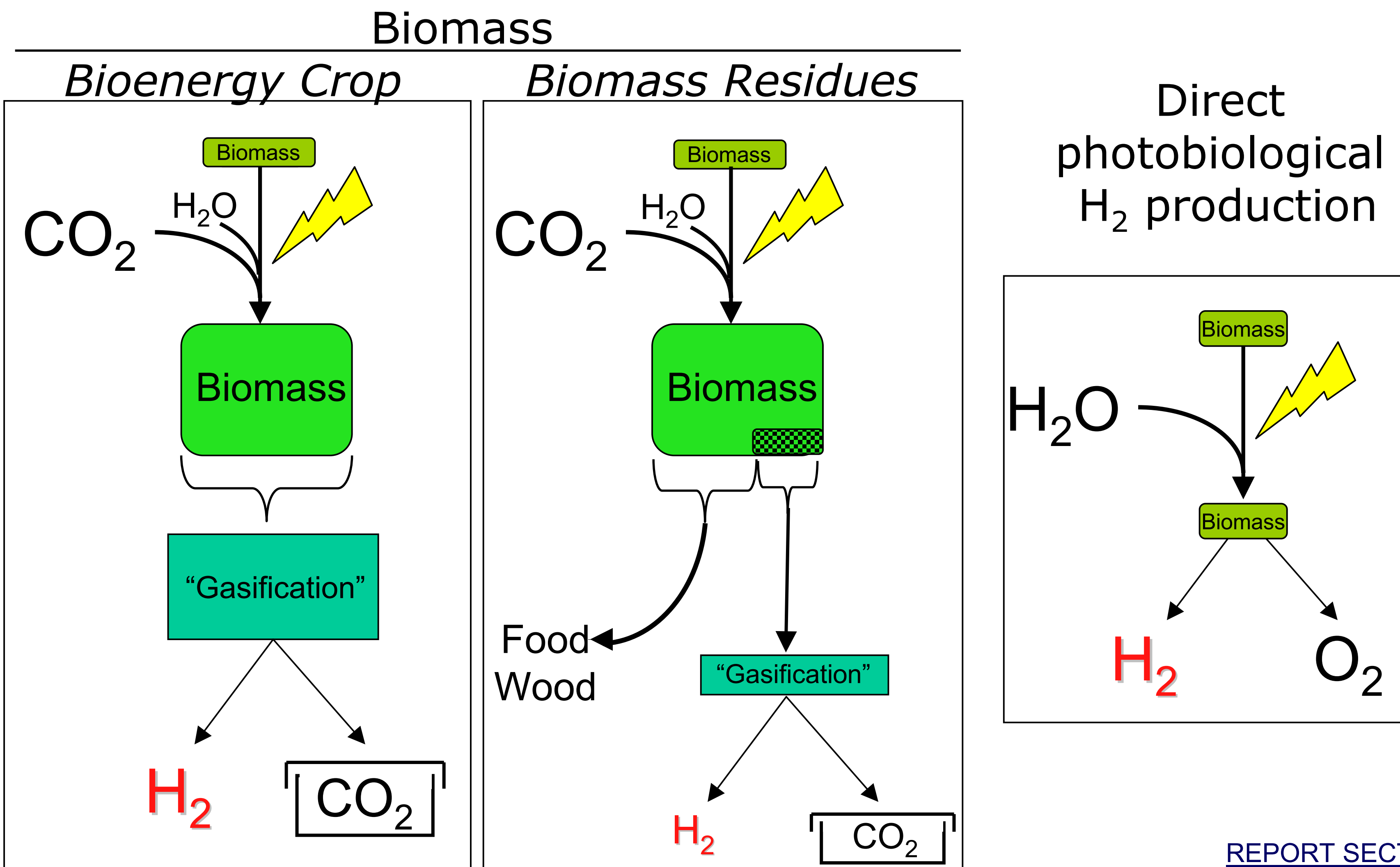
REPORT SECTIONS

HYDROGEN FROM WIND ENERGY
Findings and Recommendations

- Energy security and environmental quality both addressed by wind-hydrogen systems
- Wind has the potential to play an important role, particularly during the transition and possibly in the long term
- Wind-electrolysis-hydrogen systems yet to be fully optimized
  - Systems need to be an important element in R&D program and should be better integrated into production strategy
  - Plan should address how to best partner with industry to create robust, efficient, and cost-effective systems that will be ready for deployment as the distributed H_2 infrastructure begins to develop
  - Co-production of hydrogen and electricity needs to be further analyzed and integrated into future hydrogen production strategies

REPORT SECTIONS

HYDROGEN FROM BIOMASS AND PHOTOBIOLOGICAL PROCESSES



REPORT SECTIONS

BIOMASS AND PHOTOBIOLOGICAL PROCESSES
Findings

- Biomass-to-hydrogen conversion
  - Low thermodynamic efficiency
  - High costs of bioenergy crop production and biomass gasification
  - Significant demand for land
  - Significant impact on land use and natural resources for bioenergy crop farming

- Focus on high thermodynamic efficiency and high rates for direct photobiological H_2 production
  - Engineering of (micro)organisms and processes for hydrogen production without biomass as an intermediate

REPORT SECTIONS

BIOMASS AND PHOTOBIOLOGICAL PROCESSES
Recommendations

- De-emphasize the current biomass gasification program and refocus bio-based program to more fundamental research on photosynthetic microbial systems to produce hydrogen from water at high rate and efficiency
- Encourage innovative approaches and make use of important breakthroughs in molecular, genomic and bioengineering research
- Research and development for co-firing of biomass, e.g., with coal, coupled to subsequent carbon sequestration should continue
- Resist pressure for premature demonstration projects of developing technologies

REPORT SECTIONS

HYDROGEN FROM SOLAR ENERGY
Overview of Issues

- Potential to provide long term solution
- Direct H_2 from solar in embryonic stage
- Solar to electricity to H_2 feasible but expensive (~ \$28/kg of H_2)
  - PV for Solar to Electricity ~ \$3/W
  - Electrolyzer Cost ~ \$1/W
- Greater than 85% of current PV modules are crystalline silicon based
- Major cost for thin film in manufacturing
- Many new technologies are emerging

REPORT SECTIONS

HYDROGEN FROM SOLAR ENERGY
Findings

- Aggressive targets are needed for PV hydrogen production (2¢-4¢/kWh)
- For a potentially competitive photoelectrochemical method, the cost target should be 4¢ to 5¢/kWh
- Material cost in crystalline PV modules too high to meet cost targets
- Alternate technologies based on thin film and other emerging methods have greater potential
- No one technology is a clear winner
- Expected decline in future electrolyzer cost makes PV module route competitive

REPORT SECTIONS

HYDROGEN FROM SOLAR ENERGY
Recommendations

- Multiple development paths must be pursued until a winning technology emerges
- Along with direct photoelectrochemical methods, electricity plus electrolyzer should also be pursued
- Alternate new technologies must be investigated (e.g. polymeric, Grätzel cells, etc.)
- Novel methods to reduce manufacturing cost of some promising technologies must be developed (e.g. thin-film)
- A more aggressive target of less than $500/kW should be set

REPORT SECTIONS

CROSSCUTTING ISSUES
Program Management & Systems Analysis

- Hydrogen program management is the biggest challenge yet faced in DOE's civilian energy programs, because there are many paths to a possible hydrogen economy with many inter-related elements
- Integration of program elements would benefit from NASA & DOD tools to
  - Define & validate program requirements
  - Identify and validate interfaces
  - Identify risks & mitigation approaches
  - Support informed decision-making
  - Verify that results meet requirements
- It is essential to treat hydrogen energy development as a system, ranging from creation and production to transportation, storage, and end use
- All aspects of the various conceivable hydrogen system pathways must be modeled to understand the complex interactions between components, system costs, environmental impacts of individual components and the system as a whole

REPORT SECTIONS

PROGRAM MANAGEMENT & SYSTEMS ANALYSIS
Findings

Pathway to H_2 economy is not simple or straightforward

- Extensive R&D is needed
  - Exploratory research is essential to success
  - Manage outside the hydrogen program with targets set to be consistent with the hydrogen program
- Issues are economic, social, & public acceptance, especially safety
- Management of the hydrogen program is far more challenging than any previously undertaken by DOE in civilian energy
  - The adoption of system integration techniques used elsewhere in government has great potential for DOE hydrogen management
  - An independent, well-funded specially staffed and managed systems analysis function must be "firewall" separated to be and to appear independent

REPORT SECTIONS

PROGRAM MANAGEMENT & SYSTEMS ANALYSIS
Recommendations

- The hydrogen economy may not be the most attractive long-range option for the U.S – all long-term energy options need attention & systems analysis

- DOE should identify systems management approaches developed elsewhere in government – adapt and apply them in the hydrogen program

- Establish an independent systems analysis group to identify, assess, define gaps, evaluate results, and assist in program prioritization

REPORT SECTIONS

CROSSCUTTING ISSUES
Hydrogen Safety

- An issue for both the transition and mature H_2 economy
  - Will either be resolved or there will be no H_2 economy
- By itself, attention to safety cannot draw H_2 into marketplace; but poorly addressed, will pose formidable barrier
- Three Goals:
  1. Protect human life and property
  2. Develop codes and standards that:
     - Allow economic siting of facilities
     - Enable innovation
     - Encourage competition
  3. Develop capabilities in local zoning and emergency response officials

REPORT SECTIONS

HYDROGEN SAFETY
Recommendations

- Form specific safety objectives early in commercialization process
  - Relate to fuel alternatives, like gasoline
  - Involve stakeholder groups
  - Emphasize transition technologies first
- Independent systems analysis group should consider safety in weighing merits of alternative systems
- Training of local safety authorities should proceed in pace with commercial development
  - Prepare model safety programs in consonance with local authorities
- Develop rigorous physical testing program
  - Goal: identify and quantify safety issues rather than convince the public

REPORT SECTIONS

TRANSITION MATTERS
The Problem

- The "first mover problem"
  - H_2 suppliers won't invest without demonstrated demand
  - Without ubiquitous supply, risk increases for customers of devices that use H_2
- Policy issue: how to stimulate both sides of the H_2 market

REPORT SECTIONS

TRANSITION MATTERS
The Lessons of Experience

- In other industries, a compelling customer application drove market change

- Personal computer
  - Spreadsheet application (Visi-calc) enabled transition for PC to become working tool

- Automobile
  - Superior customer value enabled gasoline engine to win over electric (no long trip capability) and steam (affordability)

REPORT SECTIONS

TRANSITION MATTERS
The Value of Market Intelligence

- Observation of energy markets can inform transition strategies
- Niche markets most important
  - Every technology starts there
  - Most also finish there
- Observe early-stage investment markets
- Integrate with systems analysis capability

REPORT SECTIONS

TRANSITION MATTERS
Implications for Strategy

- Government as first customer
  - Defense applications?
  - Army program: http://www.onpoint.us/
- Distributed generation of H_2 matches supply with demand
- Buy-down for H_2 using technologies
- Remove safety as an issue

REPORT SECTIONS

TRANSITION MATTERS
Questions to be Resolved

- Should the DOE seek to guide the transition into selected pathways, or let development be guided by industrial stakeholders?
- Which transitional technologies to pursue?
- What incentives will entrepreneurs and investors need before they commit capital?

REPORT SECTIONS